Geoacoustic Inversion and the Evaluation of Model and Parameter Uncertainties

W.S. Hodgkiss and P. Gerstoft
Marine Physical Laboratory
Scripps Institution of Oceanography
La Jolla, CA 92093-0701
phone: (858) 534-1798 / (858) 534-7768 fax: (858) 822-0665
email: whodgkiss@ucsd.edu / gerstoft@ucsd.edu

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LONG-TERM GOALS

The development of new geoacoustic inversion methods, their use in the analysis of shallow water experimental data, and evaluation of geoacoustic model and parameter uncertainties including the mapping of these uncertainties through to system performance uncertainties.

OBJECTIVES

The development of methods for estimating the entire posteriori probability densities of the geoacoustic parameters being investigated along with the mapping of these parameter uncertainties through to characterizations of applied interest (e.g. transmission loss), the development of new geoacoustic inversion procedures for use into the kHz frequency regime, the use of ambient noise for initial estimation of seafloor layering structure, and the demonstration of these methods in the analysis of data collected during the Shallow Water 2006 (SW06) experiment.

APPROACH

Geoacoustic inversion involves a number of components: (a) representation of the ocean environment, (b) the inversion procedure selected (e.g. genetic algorithm or simulated annealing) including the forward propagation model implemented, and (c) the estimation of uncertainties associated with the parameter estimates. The latter is critical to facilitate the mapping of these uncertainties into characterizations of applied interest including the prediction of total system performance.

The reporting of geoacoustic parameter estimates without their associated uncertainties is of limited value. Of substantial greater utility is the complete *a posteriori* probability density (in general, the joint density between all parameters being estimated). One significant benefit of obtaining accurate *a posteriori* densities of the geoacoustic parameters is the potential to map these through to characterizations of applied interest (e.g. transmission loss, source detection and localization performance, etc.) in order to quantify those uncertainties as well.

Substantial experience exists in the application of full-field geoacoustic inversion methods. These have been implemented in a number of geometries (e.g. fixed vertical and horizontal arrays, towed arrays, and sonobuoys) and have been shown to work well at low frequencies (< 1 kHz). The application of these methods at higher frequencies (into the few kHz frequency regime) is at an early stage. New methods are required which are robust to modest geoacoustic heterogeneity (seafloor parameters as

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14. ABSTRACT
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well as bathymetry) and temporal fluctuations (sound speed structure, surface waves, and array dynamics).

Ambient noise provides a natural illumination source that can be used for waveguide parameter estimation purposes. Our specific interest here is in the use of ambient noise to provide initial estimates of seafloor layering structure. Rough estimates of seafloor bathymetry and sediment thickness are needed to parameterize the waveguide model prior to carrying out a geoacoustic inversion procedure regardless of the type of data used for the inversion itself (e.g. source tow data, the radiated signature of ships of opportunity, or ambient noise).

The Shallow Water 2006 experiment took place in July-September 2006 on the outer edge of the New Jersey continental shelf in approximately 80 m deep water. Both narrowband and broadband transmissions (source tows and stations) were made over a wide range of frequencies (50 Hz – 5 kHz) including detailed measurements of seafloor structure and water column variability. These data are available for geoacoustic inversion purposes and the investigation of how nuisance parameter uncertainty (e.g. water column sound speed variability) couples into seafloor parameter uncertainty.

WORK COMPLETED

The Shallow Water 2006 experiment took place in August-September 2006. One component of our analysis has focused on the effect of ocean sound speed uncertainty on geoacoustic inversion along a relatively range-independent bathymetric track [1]. Significant sound speed variations were observed at the source and receiving array and this motivated investigating several environmental parameterizations for the inversion that incorporated data from eight tonals between 53 Hz and 703 Hz.

A second area of SW06 data analysis has been to look at the spectral structure of low frequency ambient noise during storm events. Of specific interest was the seismoacoustic noise generated by tropical storms Ernesto and Florence in late-August and early-September, respectively [2]. Ernesto passed over the coastal shallow water SW06 region while Florence produced large waves in deep water to the east. Spectra observed on the SWAMI-32, SWAMI-52, and SHARK hydrophone arrays at the SW06 site were compared with those from the broadband seismic station HRV (Harvard) in Massachusetts.

Additional analysis of SW06 ambient noise data has involved using broadband cross-correlations between seafloor horizontal line array (HLA) hydrophones to estimate the time-domain Green's function between them. An analysis of SWAMI-32 data suggests that an apparent change in HLA channel order occurred during tropical storm Ernesto [3]. A further analysis provided a more comprehensive look at noise cross-correlations between HLA/VLA hydrophones in the SWAMI-32, SWAMI-52, and SHARK arrays over the 20-100 Hz band [4]. In this case, both direct path as well as higher-order arrivals could be identified.

In a third component of SW06 analysis, short-range broadband transmissions observed on a MPL vertical line array (VLA) were used to carry out a travel time geoacoustic inversion [5]. In this case, the source range was 230 m from the VLA and the source depth was varied from 15 m to 65 m to provide a wide range of grazing angles. A ray-tracing method combined with a hybrid optimization algorithm was used to invert for sediment properties.

Finally, we have explored the impact of spatial aliasing on the use of vertical array coherent ambient noise processing for estimation of seafloor layering [6]. Here, the cross-correlation of upward and downward pointing VLA beams observing ambient noise was used to extract the seabed layer structure (i.e. a passive fathometer).

RESULTS

Uncertainty in ocean sound speed profiles has significant impact on matched-field geoacoustic inversion. Although the goal of inversions is to infer the geoacoustic properties of the sea floor based on acoustic field observations received on an array, uncertainty resulting from temporal and spatial variability of the ocean sound speed plays an important role in the estimation of geoacoustic parameters and their uncertainties, especially for higher frequencies.

The data discussed here was collected during SW06 over a relatively range-independent bathymetric track where the water depth was approximately 80 m and range from source to VLA was 1 km [1]. Significant sound speed variations were observed at the source and receiving array and this motivated investigating several environmental parameterizations for the inversion.

Fig. 1 shows the range-dependent parameterization of the SW06 environment used for the inversion along with measured sound speed profiles near the time of the transmissions. For the data analyzed, the source was deployed from the R/V Knorr at WP21 to a depth of 30 m. The 16-element VLA had a total aperture of 56.25 m and was moored to the seafloor with the lowest element 8.2 m above the bottom. The inversion incorporated data from eight tonals between 53 Hz and 703 Hz.

The baseline model parameters were divided into three subsets: (a) geoacoustic, (b) geometrical, and (c) ocean sound speed. The geoacoustic model was assumed to be range-independent with a sediment layer overlying a basement. The geometric parameters included in the inversions were the source range, source depth, water depth, distance of the first array element from the bottom, and array tilt. The ocean sound speed profile was parameterized by the first three empirical orthogonal function (EOF) coefficients. The EOF basis functions were derived from 16 CTD casts taken along the 80 m isobath during a 4-day period that included the data analyzed. Fig. 2 summarizes the analysis and the first three EOFs.

Five inversion models were tested for their ability to characterize the environment with three being range-independent (RI) and two being range-dependent (RD). All models used the same geoacoustic and geometric parameters except for water depth (WD). The models differed in how they characterized the water column.

In RI-1, the sound speed profile measured at the source 5 min prior to the transmission (CTD2150) was used. In RI-2, the sounds speed profile measured at the VLA (CTD1955) was used. Lastly, in RI-3, three EOF coefficients were estimated as part of the inversion. For the range-dependent models, the water depths at both the source and VLA were included in the inversion. In RD-1, the measured sound speed profiles at the source and VLA were used. In RD-2, these are replaced by two sets of EOF coefficients which are estimated in the inversion.

Based on evaluating an objective function quantifying the discrepancy between the measured acoustic and modeled replica fields, it was determined that RI-3 and RD-2 had similar performance. Model RD-2 was selected for further parameter uncertainty analysis using a Markov chain Monte Carlo method

based on the Metropolis-Hastings algorithm. The inversion results are in very good agreement with the sandy bottom geoacoustic properties indicated by *in situ* measurements.
Some of the inversion results are illustrated in Fig. 3. The estimated sound speed profiles (Fig. 3a) at the source (thick dashed) and at the VLA (thin dashed) are very similar to each other and resemble the measured profile at the VLA (thin solid). Fig. 3b also shows good agreement between the measured (solid) and modeled (dashed) acoustic fields for the frequencies used in the inversion. At short range, it appears that the acoustic field is not particularly sensitive to the range-dependent ocean sound speed structure, and an equivalent range-independent sound speed model may be sufficient for describing the environment.

IMPACT / APPLICATIONS

Geoacoustic inversion techniques are of general interest for the estimation of waveguide parameters thus facilitating system performance prediction in shallow water. Natural transition paths for these results will be the PEO-C4I Battlespace Awareness and Information Operations Program Office (PMW-120) and the Naval Oceanographic Office.

RELATED PROJECTS

This project is one of several sponsored by ONR Code 321OA to participate in the Shallow Water 2006 experiment and participate in the analysis of the resulting data.

PUBLICATIONS

[1] Huang, CF, P Gerstoft, and WS Hodgkiss, Effect of ocean sound speed uncertainty on matched-field geoacoustic inversion, J Acoust. Soc. Am. 123(6): EL162-EL168, DOI: 10.1121/1.2908406 (2008). [published, refereed]

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[5] Y-M. Jiang, N.R. Chapman, and P. Gerstoft, "Short range travel time geoacoustic inversion with vertical line array," J. Acoust. Soc. Am. 124(3): EL135-EL140, DOI: 10.1121/1.2963093 (2008). [published, refereed]

[6] P. Gerstoft, W.S. Hodgkiss, M. Siderius, C-F. Huang, C.H. Harrison, "Passive fathometer processing," J Acoust. Soc. Am. 123(3): 1297-1305, DOI: 10.1121/1.2831930 (2008). [published, refereed]

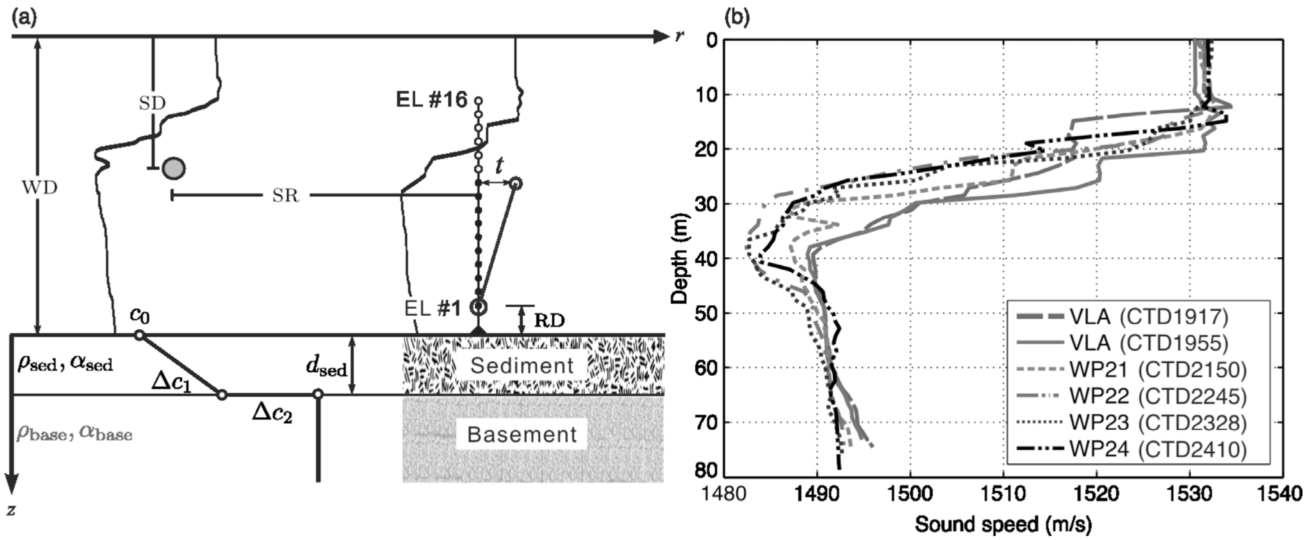

Figure 1. (a) Range-dependent parameterization of the SW06 environment. (b) Measured sound speed profiles during the acoustic transmissions. The times when the CTDs were taken are indicated as a suffix.

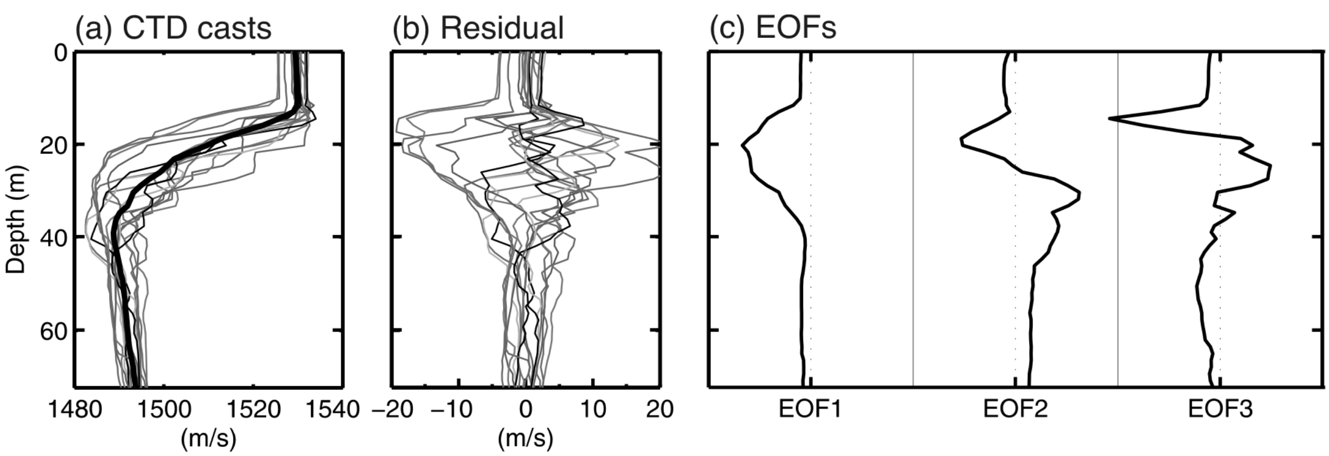

Figure 2. EOF analysis for the SW06 CTD casts. (a) Sound speed profiles measured from the R/V Knorr and the average sound speed profile (thick line). (b) Residual sound speed profiles. (c) First three EOFs.

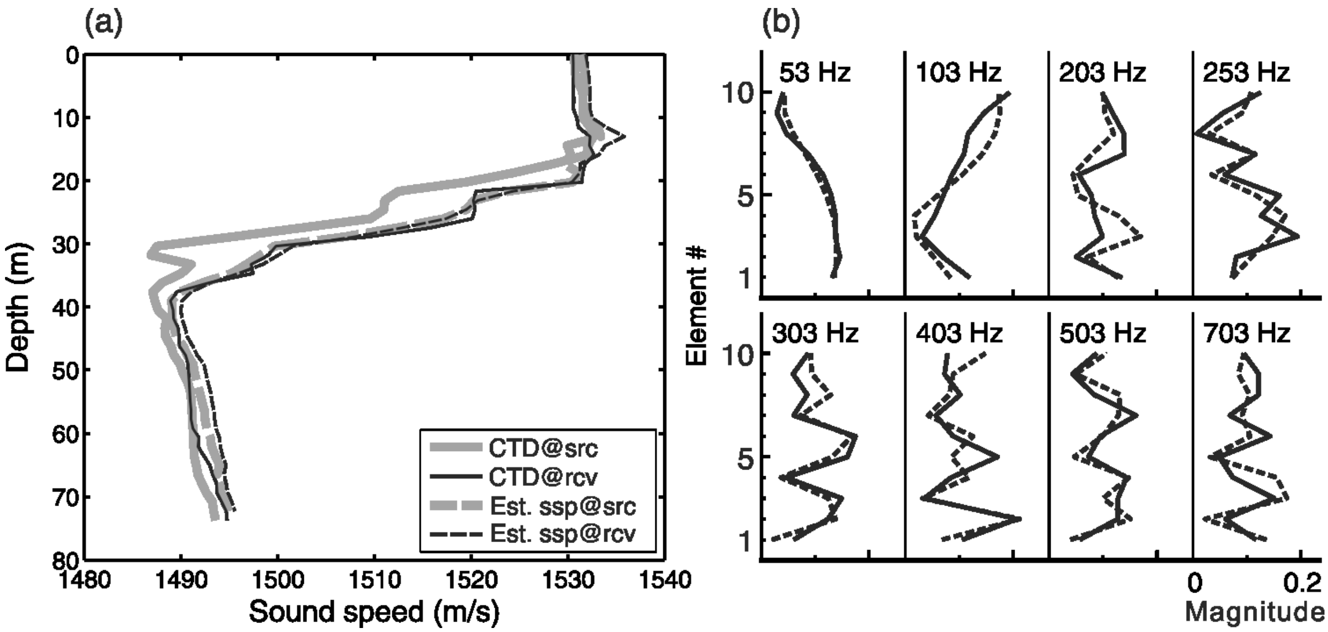

Figure 3. Inversion results for RD-2. (a) Estimated sound speed profiles. (b) Comparison of the measured (solid) and modeled (dashed) sound fields on the vertical array for each of the frequencies used in the inversion.